The Observed Building Damage Associated with Fault Movement in 1999 Chi-Chi (Taiwan) Earthquake

H. W. Yang
THSRC, Taiwan

S. M. Lin
National Taiwan Normal University, Taiwan

Daniel Chu
Ninyo and Moore, Irvine, CA

The Observed Building Damage Associated with Fault Movement in 1999 Chi-Chi (Taiwan) Earthquake

H.W. Yang
THSRC
Taiwan

S.M. Lin
National Taiwan Normal University
Taiwan

Daniel Chu
Ninyo and Moore
Irvine, California, USA-92618

ABSTRACT

The Chi-Chi earthquake caused severe damage of many buildings primarily due to surface faulting and ground shaking. It has been reported that about 10,000 buildings collapsed and 8000 buildings suffered varying degrees of damage. The observed damage to buildings resulted from many factors that include ground movement, acceleration, design code, and construction quality. The damage to buildings near the fault was attributed primarily to the ground movement. One observed phenomenon is that the damage in the up-lifted side (east side) of the rupture fault was much more severe than the opposing side (west side) of the fault mainly due to upward movement, surface tension, and surface faulting. This paper will summarize the raw data of observed damage along both sides_of the ruptured fault based upon assessment work performed on site in the Wu-Fong Township area to compare the damage quantitatively on the up-lifted side and the opposing side of the fault. The results of this study will provide insight into the building failures along the fault line.

INTRODUCTION

The Chi-Chi earthquake, which occurred in Taiwan on September 21, 1999, had a magnitude of 7.3 on the Richter Scale. This earthquake was associated with the Chelungpu and Shuangtung faults in Western Taiwan. As indicated in Fig. 1 (Ho, 1986), these two faults are 10 km apart and sub-parallel. The hypocenter at Chi-Chi lies very close to the intersection of the Shuantung fault and the Chelungpu fault. The earthquake occurred at a depth of approximately 10 km (J.G. Liou and L.Y. Hsiao, 1999). It was also indicated that the Shuantung fault was first pushed westward and ruptured, which in turn triggered the rupture of the Chelungpu fault. The Chelungpu fault which extends NS for more than 80 km caused significant damage along the ruptured fault and in nearby urban areas. Primarily surface faulting and ground shaking caused the damage to residential buildings, lifelines, dams, and transportation systems. It was reported that about 10,000 buildings collapsed and 8,000 buildings suffered damages of varying degree in this event. Damage was observed along the both sides of the ruptured faults. One distinctive damage pattern noticed was the damage that occurred on the up-lifted side of the thrust fault was more severe than on the opposing side of the fault. This paper will summarize the damage assessment work conducted in the Wu-Fong area to build a mechanism using available data that demonstrates the difference of the observed damage level between the uplifted and the opposing sides of the ruptured thrust fault. The Public Works Department of Wu-Fong Township provided the building damage assessment data. The base map showing the elevation and location of fault rupture line in 1: 1000 scale was prepared by the National Center for Research on Earthquake Engineering. Approximately 5000 individual building assessment surveys in Wu-Fong were reviewed. Types of buildings inspected include mud brick, RC framed, and steel portal framed industrial structures.

CRITERIA

The extent of the damage in the Wu-Fong area caused by the Chi-Chi earthquake and the subsequent survey of that damage provided large amounts of data regarding structural failure of buildings along the fault. The large amount of physically recorded data makes it necessary to establish criteria to select applicable observations without biasing the results. Applying these criteria to the data allows meaningful conclusions to be reached without compromising this study.

These criteria are:

1) Select areas that experienced the same or similar acceleration to provide a fair assessment of damage on both sides of the fault;
2) Prefer areas with buildings on both sides of the fault so as not to provide bias to one side of the fault;

3) Eliminate mud brick buildings because they are not representative of modern construction methods;
4) Eliminate buildings whose failure was attributed to poor construction practices so the study is based on acceptable construction practices;
5) Eliminate illegal or add-on buildings as they do not meet present codes or laws; and
6) Eliminate buildings whose damage was caused by the failure of an adjacent building to assure the study reflects primary structure failure and not collateral damage.

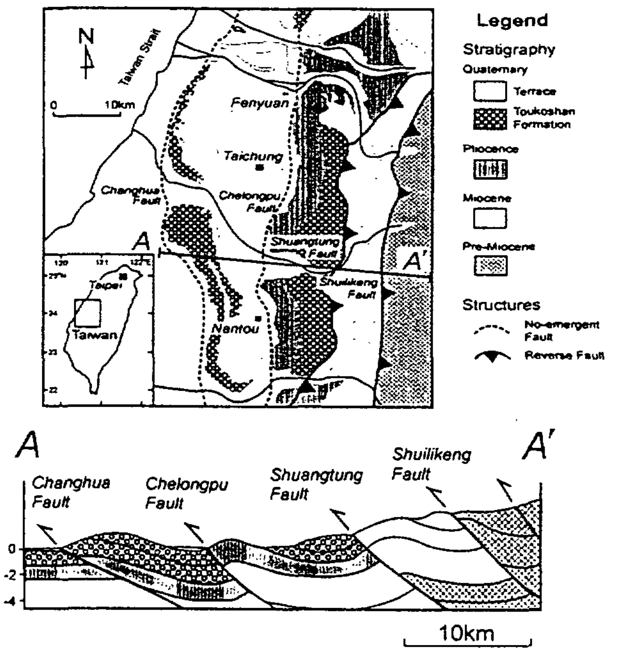

Fig.1 Schematic Map Showing the Traces and General Geology of 921 Earthquake (Ho, 1986; Lee, 1996))

STUDY AREAS

The Chi-Chi earthquake encompassed a primary damage area of 22 townships in Taichung county and Nantou county. The Wu-Fong Township, which is in the primary damage area, was selected for this study due to the extent of damage sustained and the on-site survey data taken in Wu-Fong. Wu-Fong Township was one of the more severely damaged areas in this earthquake due to the fault rupture line passing through most of the downtown area. Figure 2 shows the observed damage spatial distribution in Wu-Fong (Lin, S.M., 2000). In order to study damage patterns along both sides of the fault, three specific locations were chosen from the Wu-Fong Township based on the criteria established. A common trait of these areas includes a ruptured fault passing through the location with buildings on both sides of that fault. Figure 3 provides the three case studies utilized for this study and the location of the fault lines within those three cases.

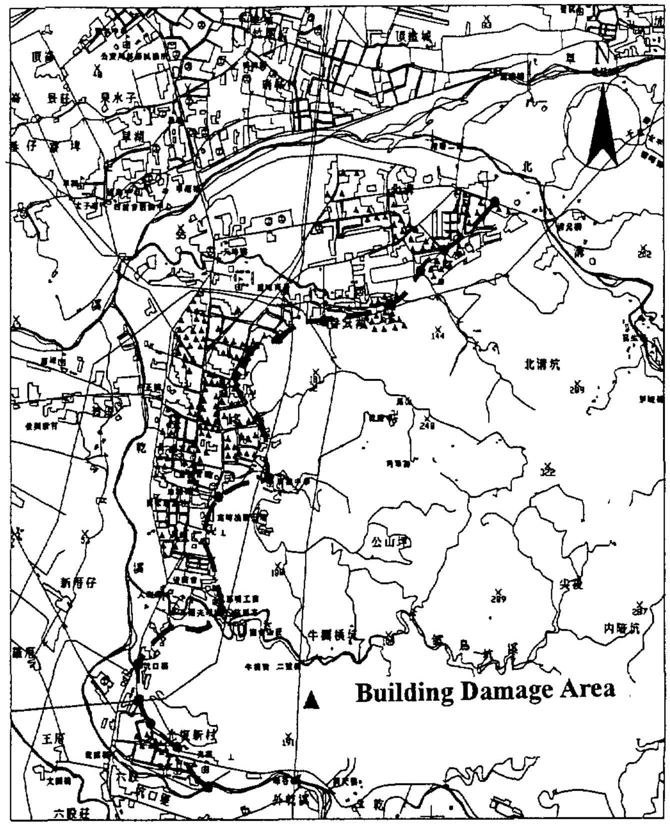

Fig. 2 Spatial Distribution of Building Damage in Wu-Fong Area (S.M., Lin, 2000)

Case 1: Wu-Fong Downtown Area

Fault rupture line passes through the east side of the downtown area. The fault rupture caused an approximate 2 meters up-lift. Most of the residential buildings on the up-lift side were totally destroyed. Only minor damage was observed for the buildings on the opposing side of the fault.

Case 2: Temple of Ten-Thousand Buddha's

A college campus and the Temple of Ten-Thousand Buddha's on the up lifted side of the fault were totally destroyed. The fault rupture is less than 100m south of the Taiwan Provincial Assembly Compound. The Assembly building located on the opposing side of the fault sustained relatively minor damage.

Case 3: Kuangfu High School

The fault rupture line passes through the Kuangfu High School campus. A thrusted fault rupture 2 meters in height is clearly visible in the sports field. A multi-story building on the uplifted side was severely damaged, while an elementary school approximately 5m from the fault line on the opposing side of the fault experienced only minor damage.

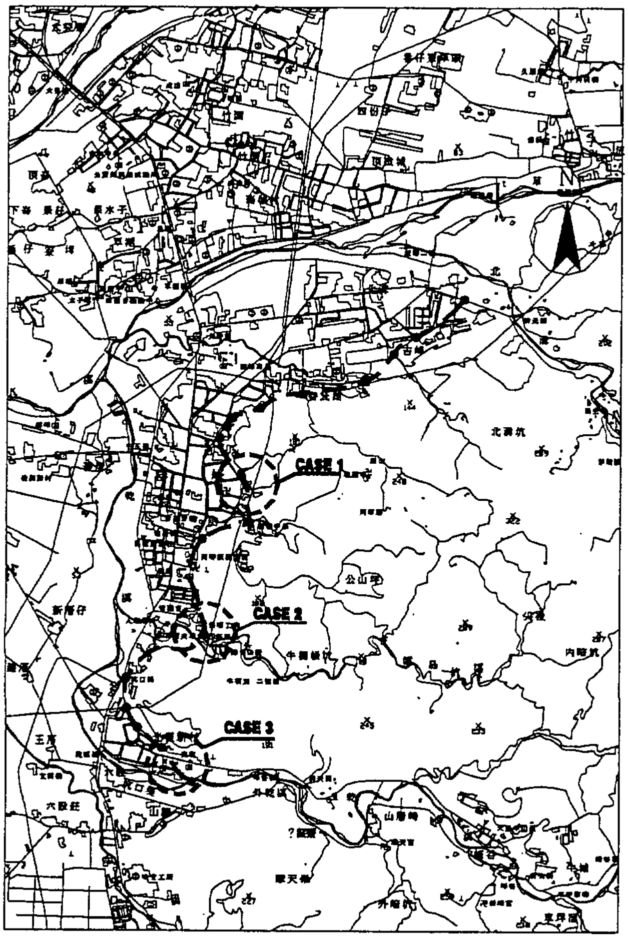

Fig. 3 Case Study Locations in Wu-Fong Area

ANALYSIS AND RESULTS

It is readily apparent that the observed damage on the up-lift side of the faults is more severe than that on the opposing side of the faults. A qualitative expression of the failure mechanism (Liu and Chen, 1999) is shown in Figure 4. Careful review and study of the visual inspections and damage assessments carried out after earthquake, lead one to believe that most of damage in the up-lift side was due to ground deformation associated with the up-lift and surface faulting. Buildings located on the opposing side of the fault (West Side) suffered much less ground deformation; therefore, only minor damage was observed.

The question is how can one quantify the observed data to provide a realistic and useful tool, which provides information that will help planning for reducing risks, caused by an earthquake.

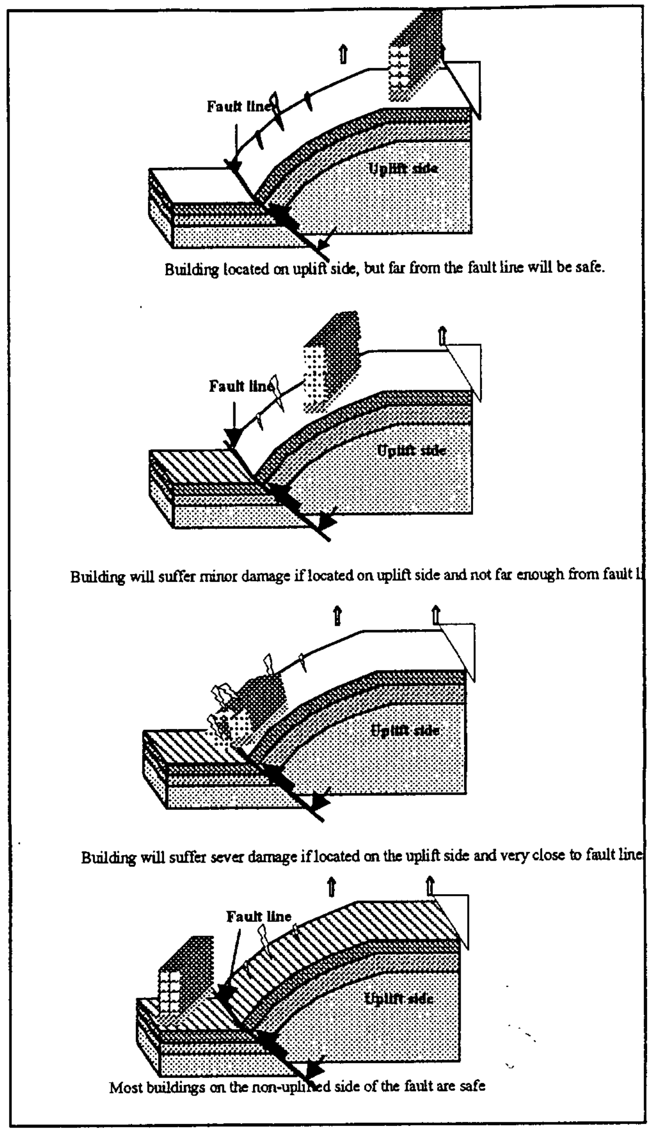

Fig. 4 Building Failure Mechanism in Chi-Chi Earthquake (Liu and Chen, 1999)

To allow quantification of the observed damage a Structure Distortion Index (SDI) was devised and used for the buildings located on both sides of the fault line. These buildings sustained either total or partial damage. Figure 5 graphically shows the SDI definition. Since the elevation and location survey done after earthquake was for urban planning purposes, it must be understood that the information of elevation may not be accurate and sufficient enough to define differential settlement that is commonly used for building foundation structural design. Higher SDI values equate to a higher damage potential for a building. In addition, it was assumed that the ground elevation was consistent prior to this earthquake. Once the SDI value, damage condition (total or partial), and relative position to the fault line are known, the SDI distribution curve for buildings on both sides of the fault line can be prepared. The damage to buildings on both side of the fault line can then be compared.

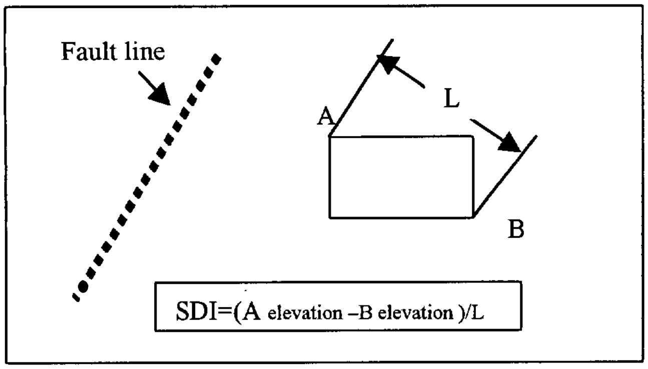

Fig. 5 Definition of Structure Distortion Index

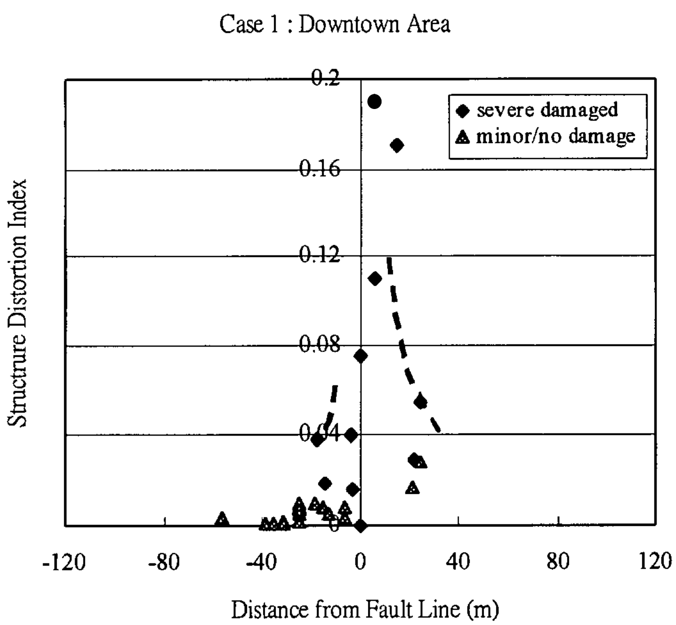

Fig. 6 Damage Distribution for Case 1

Figure 6, 7, and 8 are the SDI data distribution for case 1, 2, and 3 respectively. These three cases demonstrate the same pattern of SDI curves. In cases of buildings located on a fault rupture line, the buildings suffered severe damage and have a SDI value up to 0.2. In general, the damaged building, at roughly the same distance from fault line, has higher SDI value on the uplift side than on the opposing side of the fault. Envelopes of SDI data distribution can be generated for each side of the fault. The damage sustained within the envelope for the up-lift side is clearly higher than the damage sustained within the envelope for the opposing side, which supports the original observation. In addition, severely damaged buildings in case 3 can be found as far as 110 meters from the fault rupture line. Both case 1 and case 3 demonstrate that many buildings survived with minimal damage on the west side of fault line.

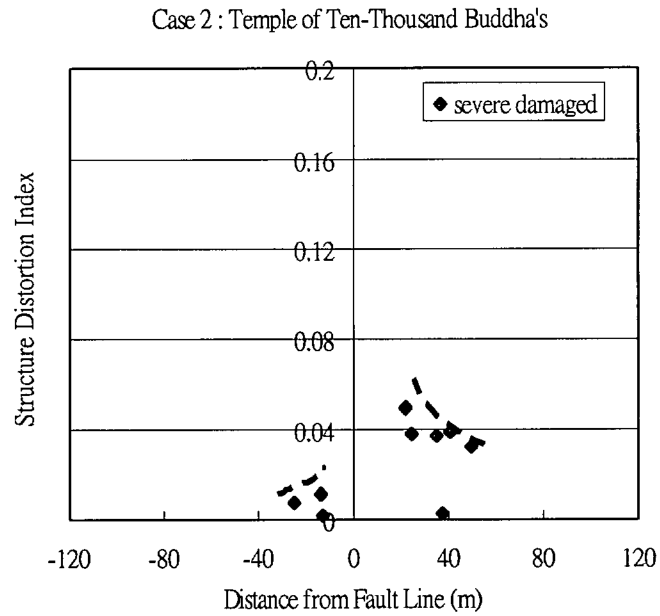

Fig. 7 Damage Distribution for Case 2

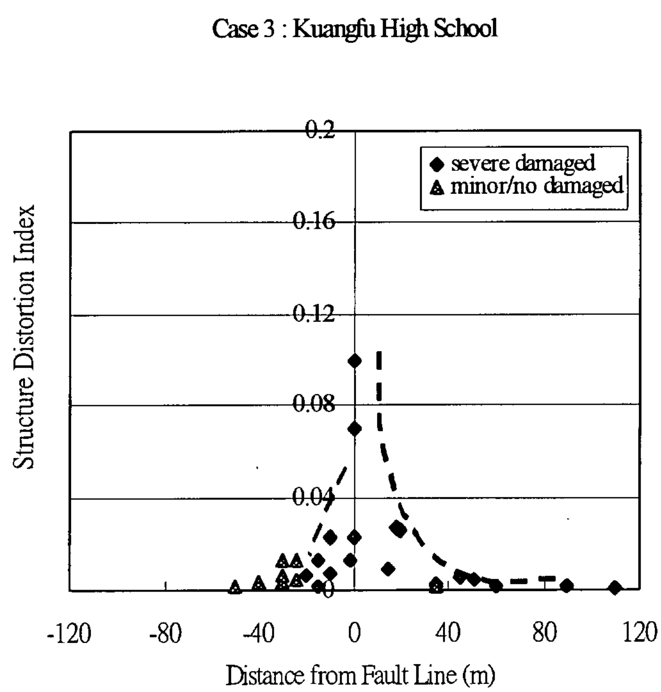

Fig. 8 Damage Distribution for Case 3

CONCLUSIONS

It is readily apparent from the SDI data distribution and resulting envelopes for the case studies that no building is safe when that building crosses a fault that experiences ruptures like those the Chi-Chi earthquake produced. This study demonstrates quantitatively that the damage to buildings was more extensive on the uplifted side of the fault. It is also clear that the nearer a building is to the fault on the uplifted side, the more extensive the damage to be expected.
This study reaches conclusions based on the Chi-Chi earthquake data and as such one should exercise caution in extrapolating any similarities to larger magnitude earthquakes. It must be considered that the sample data is limited and more extensive research should be conducted not only from this event, but other large magnitude earthquakes around the world to provide a more comprehensive database, which it is believed would provide a valuable tool for establishing potential risks to buildings. This could reduce the risk of loss of buildings and life not just in Taiwan but across the globe.

REFERENCE

1. Lin, H.M. [2000]. The Spatial Distribution of Damage in 921 Earthquake Event (in Chinese), Department of Geology, Taiwan National Normal University.
2. National Center for Research on Earthquake Engineering, [1999]. Base Map for Fault Rupture Line and Construction Restriction Zone.
3. Liou, J.G. and Hsiao, L.Y. [1999]. Tectonic Setting and Regional Geology of Taiwan, REPORT#4 ON THE Chi-Chi (Taiwan) Earthquake, USGS.
4. Liu, T.K. and Chen, W.S. [1999]. 921 Earthquake Interpretative Report (in Chinese), Department of Geology, National Taiwan University.
5. National Center for Research on Earthquake Engineering, [1999]. Damage Assessment Report for 921 Earthquake.
6. Ho, C.S. [1986] An Introduction to the Geology of Taiwan : Explanatory Text of the Geologic Map of Taiwan. Central Geological Survey, Taipei, Taiwan, ROC.
7. Public Work Department of Wu-Fong Township,[2000]. 921 Earthquake Assessment Report.

ACKNOWLEDGEMENT

National Center for Research on Earthquake Engineering provided their technical assistance to all assessment teams immediately after earthquake. In addition, they built a database by compiling relevant information and make it open to public. The Center personnel were most helpful in allowing access to their information and provided invaluable assistance to this effort. Miss T. C. Lin of the National Taiwan Normal University team did the major mapping work on the base map provided by the Taiwan Construction & Planning Administration, Ministry of Interior. Her assistance is deeply appreciated. Mike Liu and his staff provided technical support on drawings and figures that is greatly appreciated.